SCOUR DOWNSTREAM OF A BLOCK RAMP IN ASYMMETRIC STILLING BASINS

Stefano PAGLIARA¹ and Michele PALERMO²

¹Professor, Dept. of Civil Eng., University of Pisa
(Via Gabba 22, 56122, Pisa, Italy)
E-mail:s.pagliara@ing.unipi.it
²PhD Student, Dept. of Civil Eng., University of Pisa
(Via Gabba 22, 56122, Pisa, Italy)
E-mail:michele.palermo@ing.unipi.it

Block ramps are hydraulic structures generally used in mountains rivers. In the last decades they have become more common in river restoration as they minimize the environmental impact. Anyway, as other hydraulic structures, a scour hole forms at their toe which has to be foreseen and eventually controlled in order to avoid structural risks. The scour downstream of a block ramp in a stilling basin having the same width of the ramp was studied by many researchers who proposed relationships in order to evaluate the main geometrical parameters of the scour hole and ridge, but no studies are known in literature which analyze the scour mechanism downstream of a block ramp in an asymmetrically enlarged stilling basin. The aim of this study is to deepen the hydrodynamic behavior and the scour process in presence of two different asymmetrically enlarged stilling basin configurations. Tests were performed for block ramp slope 1V:8H and uniform stilling basin material. It was observed that a three dimensional scour hole forms downstream of the ramp toe when the channel bed has not the same ramp width. The maximum scour depth at equilibrium was compared to the respective ones that occurred in the same geometrical and hydrodynamic conditions in presence of stilling basin with the same ramp width. The scour depth was found much more prominent in the former case (asymmetric enlarged stilling basin) as the scour mechanism completely changes. A new useful relationship, taking into account also the effect of the downstream water level, is proposed in order to evaluate the maximum scour depth.

Key Words: Asymmetric stilling basin, Block ramp, Hydrodynamic behavior, Tailwater.

1. INTRODUCTION

Block ramps have been largely used especially in the last few decades in river restoration projects as they assure a high energy dissipation and contemporarily river bed stability. They are mainly used in mountain rivers and are made of blocks, whose mean diameters vary between 0.3 and 1.5 m, disposed on a steep bed. Generally their height is of several meters and the dissipative process takes place both on the ramp bed and in the stilling basin in which a scour hole forms. The stilling basin scour process is due to the erosive forces dissipated by vortices transporting the bed material downstream. A scour hole develops until a final equilibrium configuration is asymptotically reached (Sumer et al.¹, Canepa and Hager², Dey and Sarkar³).

Many studies are present in literature which analyze the scour mechanism and furnish useful relationships to foresee the maximum scour depth downstream of an hydraulic structure. Among these, Veronese⁴ was one of the pioneer who studied the scour phenomenon downstream of a spillway and gave empirical relations in order to evaluate the maximum scour depth. More recently, Hassan and Narayanan⁵ proposed a semi-empirical theory to predict the scour time rate for local scour downstream of an apron. Farhoudi and Smith⁶
analyzed the scour hole geometry downstream of hydraulic jump. A more detailed analysis for the scour process downstream of grade control structures was conducted by Bormann and Julien (and successively further developed by D’Agostino and Ferro) who derived equations for the main equilibrium scour hole parameters. Raudkivi and Breusers and Hoffmans and Verheij synthesized and collected many of the studies and results present in literature for scour downstream of hydraulic structures presenting practical guidelines to understand the phenomena related to scour which are useful for engineering practice. A theoretical approach based on momentum equation was developed by Hoffmans. He furnished equations to compute the maximum scour depth for both plunging and horizontal jets. Anyway, a more detailed analysis on both structural failure and scour mechanism related to block ramps can be found in recent literature. The former problem was investigated by Whittaker and Jäggi who analyzed the equilibrium condition of a ramp and the structural failure mechanisms. Pagliara and Hager analysed the scour mechanism downstream of block ramps for uniform bed material. The effect of channel bed material non-uniformity on scour mechanism was deepened by Pagliara who also analysed the jump type which can occur downstream of the ramp toe. Successively, Pagliara and Palermo analyzed the effect of the introduction of rock-sills in the stilling basin on scour geometry in presence of both uniform and non-uniform stilling basin material, respectively and proposed some useful equations to evaluate both scour depth and length. Anyway, all the mentioned studies focus on the scour mechanism occurring downstream of a ramp toe in either protected or unprotected stilling basin, but limited to the case in which the ramp width is the same of the downstream stream reach. In all these cases a quasi two-dimensional scour hole forms.

The present paper aims to analyze the scour mechanism and the hydrodynamic behaviour in presence of an asymmetrically enlarged stilling basin downstream of block ramp in various tailwater condition, in clear water condition and when an $F_{MB}$ jump type (free jump in mobile bed, see also Pagliara) occurs. Figs 1a-b-c-d illustrate a sketch of the model used for experiments in which the main geometrical parameters of the scour hole are shown (Fig 1a) the various asymmetric tested configuration are schematized (Figs 1b-c-d).

2. EXPERIMENTAL SET-UP

The experiments were conducted at the Hydraulic Laboratory of the University of Pisa, Italy. Tests were carried out in a rectangular channel 0.35 m wide, 6 m long and 0.50 m high. The ramps used in the experiments were made of inox steel sheet on which two different granular materials were glued in order to simulate ramp bed. Ramp width was 0.15 m. The material used for ramp bed were A1 and A2, whose granulometric characteristics are the following: $D_{50(A1)}=0.02401\,\text{m}$, $D_{50(A2)}=0.01480\,\text{m}$, $D_{90(A1)}=0.02604\,\text{m}$ and $\sigma=(D_{84(A1)}/D_{16(A1)})^{0.5}=1.11$ for material A1 and $D_{50(A2)}=0.02604\,\text{m}$, $D_{90(A2)}=0.01786\,\text{m}$ and $\sigma=(D_{84(A2)}/D_{16(A2)})^{0.5}=1.31$ for material A2. $D_{x}$ represents the characteristic diameter of the ramp material for which $xx\%$ of sediment is finer and $\sigma$ is the non-uniformity parameter.

For channel bed, one uniform granular material ($m1$) was tested. The granulometric characteristics of material $m1$ are the following: $d_{16}=0.00435\,\text{m}$, $d_{50}=0.00575\,\text{m}$, $d_{84}=0.00624\,\text{m}$, $d_{90}=0.00741\,\text{m}$ and $d_{90}=0.00741\,\text{m}$ and...
The analysis of the scour process in the case in which the width of the channel is the same of the ramp was conducted by Pagliara in his study the tailwater effect was taken into account and it was observed that it is prominent. In fact, in the same hydraulic condition the scour depth results to be less if tailwater increases. The increase of downstream water level in fact increases the length of flow diffusion in the scour hole resulting in reduced hydrodynamic forces acting on the bed (see also Hoffmans and Julien). Therefore, by applying the Buckingham $\Pi$-theorem and rearranging the non-dimensional parameters yields:

$$Z_{\text{max}} + T_w = \frac{z_{\text{max}} + h_0}{h_1} = f(F_{d90})$$ (2)

Functional relation (2) is valid in the case in which the width of the channel is the same of the ramp ($B/b=1$), and the parameters $\sigma$ and $i$ present in the functional relation (1) are not taken into account as only one uniform material and one ramp slope were tested. If one considers the case in which the channel is asymmetrically enlarged another non dimensional parameter has to be included in the functional relation (2) resulting in:

$$Z_{\text{max}} + T_w = \frac{z_{\text{max}} + h_0}{h_1} = f(F_{d90}, B/b)$$ (3)

in which the parameter $B/b$ takes into account the effect of the different widths.

It was observed that the effect of the enlargement on the scour geometry and on the hydrodynamic of the phenomenon is very prominent. In fact the scour mechanism and its shape completely changes. When...
$B/b=1$ the scour hole has a regular and symmetric shape, moreover the scour results to be almost two dimensional, meaning that, especially for high discharges, the maximum scour depth is very close to the average depth evaluated in the transversal section in which the maximum scour occurs. Vice versa, if we consider the asymmetric enlarged channel, the scour hole results to be strongly three dimensional, as shown in Fig 4. This is due to the fact that the sudden enlargement determines a deflection of the flow pattern downstream of the ramp toe. In fact, observing Fig. 3, it appears evident that an almost circular ridge forms, which constitutes an obstacle for flow passage which is partially re-directed toward the ramp toe (zone of inverted flow).

In this zone a counter clockwise water circulation takes place and this leads both to a deflection and a concentration of the water flow exiting from the ramp toe, resulting in an increase of the erosive water capacity.

In all experiments, in fact, it was noted that, in the same hydraulic conditions the effect of enlargement is to increase the scour depth.

Basing on these observations and on dimensional analysis, the non dimensional group $Z_{max} + T_w$ was plotted versus $F_{d90}$ for different ratios $B/b$ (see Fig. 5).

It can be noted that, in the tested range, $Z_{max} + T_w$ is a monotonic increasing function of $F_{d90}$; moreover, in the same hydraulic conditions (i.e. for the same value of $F_{d90}$), $Z_{max} + T_w$ increases if $B/b$ increases. The following general equation is proposed to evaluate $Z_{max} + T_w$:

$$Z_{max} + T_w = rac{z_{max} + h_0}{h_1} = A \exp(CF_{d90}) \tag{4}$$

in which $A$ and $C$ are coefficients depending on $B/b$ that can be expressed as follows:

$$A = 0.14 \frac{B}{b} + 2.31 \tag{5}$$

and

$$C = 0.1 \frac{B}{b} - 0.04 \tag{6}$$

Substituting Eq. (5) and Eq. (6) in Eq. (4) one can evaluate $Z_{max} + T_w$. Eq. (4) is valid in the tested ranges.
of parameters, $2.5 < F_{d90} < 4.5$, $1.15 < T_s < 2.5$, $1 < B/b < 2.33$, for ramp slope $i = 0.125$ and when the jump is completely located in the stilling basin, without submerging the ramp. A simple analysis of the proposed Eq. (4) shows that if $F_{d90}$ is constant and the tailwater level increases, the non dimensional maximum scour decreases thus confirming the experimental tests and the prominent effect of tailwater level on scour mechanism. Fig. 6 compares the measured and calculated values of $Z_{max} + T_w$.

![Fig.5](image)

**Fig.5** $(Z_{max} + T_w)$ versus $F_{d90}$ for $B/b=1$, $B/b=1.67$ and $B/b=2.33$

It can be noted that the general equation proposed (Eq. 4) well predicts the parameter $Z_{max} + T_w$ as the calculated values are within a range of 20% deviation from the perfect agreement line.

![Fig.6](image)

**Fig.6** Comparison between measured and calculated values of $(Z_{max} + T_w)$ for $B/b=1$, $B/b=1.67$ and $B/b=2.33$

5. CONCLUSIONS

In the present paper the scour mechanism downstream of a block ramp in an asymmetric stilling basin was analyzed. Experiments were performed in three different channel configurations ($B/b=1$, $B/b=1.67$, $B/b=2.33$), and with different tailwater levels. It was observed that, being the same hydraulic conditions, the hydrodynamic of the phenomenon completely changes in an enlarged stilling basin. An inverted flow zone forms in the enlarged side downstream of the ramp toe. The water flow exiting from the ramp is deviated and concentrated thus contributing to increase its erosive capacity. The scour depth, in fact, results to be more prominent than in the case in which $B/b=1$ and, in the tested range, it was observed that bigger is the channel width bigger is the scour depth. On the other side, a tailwater increase causes a reduction of the scour depth. This is due to the fact that the diffusion length of the flow coming from the ramp is bigger for high tailwater thus causing a reduction of the water erosive force when it impacts the stilling bed. A novel relationship is proposed to evaluate the non dimensional parameter $Z_{max} + T_w$ which results to be a function of the densimetric Froude number and the ratio $B/b$. Further experiments can be done in order to investigate both the effect of the non uniformity of the stilling basin material and the ramp slope.

REFERENCES